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DEVELOPMENT OF ADEQUATE METEOROLOGICAL MONITORING STANDARDS FOR SAFETY ANALYSIS OF NUCLEAR FACILITIES

by

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A report prepared by E. Alp and P.J. Lewis, Concord Scientific Corporation under contract to the Atomic Energy Control Board.

ABSTRACT

The aim of this report is to identify what constitutes adequate meteorological information for airborne dispersion calculations in case of releases from nuclear facilities during "normal operation," "design postulated accidents," and "emergency situations."

The models used for estimating downwind dispersion are reviewed, including short-range simple terrain, short-range complex terrain (considering hills, valleys and coastal locations), and medium to long range models with emphasis on Lagrangian models. The meteorological input parameters required for running these models are identified.

The methods by which these parameters may be obtained from raw meteorological data are then considered. Emphasis is placed on well-tried and recommended methods rather than those which are currently being developed and lack long-term field tests.

The meteorological data required to calculate the parameters that are in turn input to dispersion calculation methods can be obtained mainly from tower measurements. Recommended tower height is 50 m, with two levels of instruments (10 and 50 m) for wind speed, wind direction and temperature. Data for precipitation and solar radiation, that may be required under certain conditions and for special calculations, may be estimated from nearby representative weather stations (if available). For simple terrain, a single tower is sufficient. For complex terrain, such as coastal regions, two towers are desirable for accurate characterization of the turbulence regime in the vicinity of a release site.

For releases during "normal operation," a minimum of one-year's on-site data are required on an hourly basis although two-years' data are desirable. For "design postulated accidents," five-years' data would be needed. For these purposes a permanent tower system is not necessary.

For actual "emergency conditions," real-time and forecast data are required. For accurate forecasts during the initial stages of a release, on-site data for up to twelve hours prior to the start of the release are highly desirable. This necessitates establishing a permanent on-site tower system.

The report provides the necessary accuracy specifications for instruments required for the meteorological measurements. Data monitoring and recording, maintenance, quality control and assurance are also discussed. Instrument accuracy specifications are based on experience of researchers and available technology. Error propagation analyses are recommended to determine the full implications of instrument accuracies on the accuracy of dispersion model predictions.

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RÉSUMÉ

Le présent rapport a pour but d'identifier ce qui constituerait une base d'information météorologique adéquate pour le calcul du taux de dispersion dans l'air des rejets provenant des installations nucléaires durant «l'exploitation normale», «les accidents hypothétiques de base» et «les situations d'urgence».

Les modèles utilisés pour estimer la dispersion sous le vent sont examinés, y compris les terrains simples et complexes de courte étendue (tenant compte des collines, des vallées et des littoraux), les modèles d'étendue moyenne et longue et particulièrement les modèles de Lagrange. Les paramètres météorologiques pour utiliser ces modèles sont aussi identifiés.

Les méthodes utilisées pour déterminer les paramètres à partir de données météorologiques brutes sont examinées. Nous avons souligné les méthodes éprouvées et recommandées plutôt que celles qui sont mises au point actuellement et qui n'ont pas encore subi d'épreuves à long terme.

Les données météorologiques nécessaires pour calculer les paramètres qui servent à leur tour de données dans les méthodes de calcul de dispersion sont obtenues principalement par les mesures du haut d'une tour. La hauteur recommandée de cette tour comportant deux niveaux munis d'instruments de mesure (10 à 50 m) pour relever la vitesse et la direction du vent et la température est de 50 m. Les données de précipitation et de rayonnement solaire, qui peuvent être nécessaires dans certaines conditions et pour des calculs spéciaux, peuvent être estimées à partir de l'information obtenue de bureaux de météo représentatifs près de l'installation, s'ils existent. Pour les terrains simples, une seule tour suffit. Par contre, deux tours sont préférables pour caractériser précisément le régime de turbulence près d'une source de rejet sur un terrain complexe, par exemple, dans les régions littorales.

En cours d'«exploitation normale», il est nécessaire de recueillir les données à chaque heure sur le site pendant au moins un an, mais il est préférable de les recueillir pendant deux ans. Dans le cas des «accidents hypothétiques de base», il est nécessaire de recueillir des données pendant au moins cinq ans. Dans ces deux cas, il n'est pas nécessaire d'avoir une tour permanente.

Dans «les situations d'urgence» réelles, des données prévues en temps réel sont requises. Pour prévoir de façon exacte les conditions pendant les étapes initiales de tout rejet, il est très souhaitable de disposer de données sur le site jusqu'à 12 heures avant le début du rejet. Dans ce cas, il faut établir une tour fixe sur le site.

Le présent rapport traite des spécifications de précision qui sont nécessaires pour les instruments requis pour les relevés météorologiques. Il traite également de la surveillance et de l'enregistrement des données, de la maintenance, ainsi que du contrôle et l'assurance de la qualité. Les spécifications de précision des instruments sont basées sur l'expérience des chercheurs et sur les techniques disponibles. Des analyses de la propagation des erreurs sont recommandées pour déterminer toutes les répercussions de la précision des instruments sur l'exactitude des prévisions des modèles de dispersion.

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DEVELOPMENT OF ADEQUATE METEOROLOGICAL MONITORING STANDARDS FOR SAFETY ANALYSES OF NUCLEAR FACILITIES

A. INTRODUCTION

This is the final report for a project carried out for the Atomic Energy Control Board (AECB No. R1100343280, DSS Contract No. OSS84-00157) by Concord Scientific Corporation.

The objective of the project is to identify what constitutes adequate meteorological information for airborne dispersion calculations in case of releases from nuclear facilities, for the differing conditions of normal operation, design postulated accidents, and emergency conditions. Here,

- "Normal operation" is taken as the day-to-day regular operation of the facility,
- "Design postulated accident" means those accident scenarios which must meet the reference dose limits of Hurst and Boyd (1972),
- "Emergency conditions" means the instantaneous state of the upset plant.

The report addresses this objective through a review of the models used for estimating downwind dispersion for the three "conditions" defined above and identifying their input requirements. Topographical effects on dispersion are also considered and models to take into account these effects are included in the review.

A distinction must be made here between the input "parameters" required by the models and the meteorological "measurements" required for the specification of these "parameters." The term input "data," as is frequently used in the literature, may mean either or both of these sets. This report deals with both the input parameters and the meteorological measurements required for dispersion calculation methods.

Chapter B presents the dispersion calculation methods and the required input parameters for the three conditions, considering different requirements for short and long ranges and for simple and complex terrain. The description of the models in this section is generally of a qualitative nature with references to appropriate literature for details. Exceptions are the equations that are necessary for the identification of the major meteorological input parameters. General familiarity with air pollution meteorology and the methods described in two CSA standards is assumed. Included in this chapter is a discussion of field study requirements for site characterization prior to finalizing the details of an on-site meteorological program.

Chapter C identifies the meteorological measurements required to specify the input parameters for the dispersion calculation methods. Details on establishing the meteorological monitoring system are given in Chapter D.

Chapter E provides a summary of recommendations and, conclusions are given in Chapter F.

B. METEOROLOGICAL INPUT PARAMETERS FOR DISPERSION CALCULATIONS

This chapter presents the dispersion calculation methods and their required input parameters for the three "conditions" namely, "normal operation," "design postulated accidents," and "emergency conditions." Different requirements for short and long ranges and for simple and complex terrain are also identified through a discussion of the important physical phenomena related to these situations and applicable models.

1. Review of Dispersion Calculation Methods

1.1 Short Range - Simple Terrain

For the purposes of this study "short range - simple terrain" is taken as the zone near a release point where curvature of air parcel trajectories is not important. This zone can be taken as the zone within 0 to 50 or 100 km from the release point where the terrain is reasonably flat and homogeneous (CSA, 1983, paragraphs 2.3.6 and 2.4.1).

The major characteristic of dispersion calculation methods used for normal operation is that they are designed for estimating long-term concentrations and deposition of the order of a month, season, or a year. Thus, they require long term hourly data, climatological averages, and/or joint frequency tables for the input parameters.

The familiar long-term Gaussian formula as described in Canadian Standards Association (CSA) Standard N288.1 (CSA, 1984, Equations 5.1 and 5.2) or N288.2 (CSA, 1983, Equation 8) can be used in dispersion calculations. This equation is reproduced here for convenience using the notation adopted for the present study:

$$C_{\text{long-term}}\ (x,\ \text{any } y \text{ within a given sector } \theta_j,\ \text{and } z = 0)$$

$$= \left(\frac{2}{\pi}\right)^{1/2} \frac{1}{x\theta_j} \sum_{ik} \frac{\dot{Q}\, F_{ijk}}{\Sigma_{zi}\, u_k} \exp\left[-\frac{1}{2}\,\frac{H^2}{\Sigma_{zi}^2}\right] f(\Sigma_z, H, h_i) \qquad (B.1)$$

Here,

- $C_{\text{long-term}}$ = ground level concentration at a distance x ($Ci \cdot m^{-3}$),
- x = downwind distance in the main wind direction from the release (point (m),
- y = lateral distance (m),
- z = height from ground (m),
- $\dot{Q}$ = activity release rate ($Ci \cdot s^{-1}$),
- θ_j = width of the sector in which C is being calculated (radians); concentration is assumed to be uniform within this sector,
- u_k = representative transport wind speed ($m \cdot s^{-1}$) for the kth wind speed class,
- Σ_{zi} = representative Σ_z for the ith stability class; Σ_z is the parameter to characterize the dispersion in the vertical

direction, a function of σ_z, the vertical dispersion parameter, corrected for building wake (as described in N288.2, Section 2.4),

F_{ijk} = frequency of joint occurrence (fraction) of hourly stability class i, hourly wind speed class k, and wind blowing in the sector subtended by θ_j within the same hour,

H = effective source height corrected for buoyancy and momentum rise, downwash, entrainment (as described in N288.2, Section 2.5).

$f(\Sigma_z,H,h_i)$ = capping inversion correction function,

h_i = height of the capping inversion (m) (mixed layer height).

It should be noted that the time integrated concentration χ (Ci·s·m^{-3}) will have the same form of Equation B.1 except that $\dot{Q}$ would be replaced by Q (Ci), the total activity released.

If hourly data are available in terms of actual wind speeds, wind directions, mixing height, dispersion parameters, etc., rather than in terms of classes ijk, then the concentration at any given receptor can be calculated using the short-term dispersion formula repeatedly for each hour that the data are available, and then averaging these contributions.

$$C_{\text{short-term}}(x,y,o) = \frac{\dot{Q}}{\pi u \Sigma_y \Sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y^2}{\Sigma_y^2} + \frac{H^2}{\Sigma_z^2}\right)\right] f(\Sigma_z,H,h_i) \quad (B.2)$$

Here Σ_y is the parameter to characterize dispersion in the horizontal direction. It is a function of σ_y, the horizontal dispersion parameter, corrected for building wake effects.

If some of the routine releases occur at times when the effective release height H is above the mixing height h_i, then contributions corresponding to such conditions should be calculated considering the possibility of fumigation, i.e., the plume being brought down from a stable layer aloft into the mixing layer and thus to ground level by the turbulence in the mixing layer. For a constant mixing height in the horizontal, calculation methods are described in N288.2 (Section 2.6.5). In case of a coastal site, however, where the mixing height varies with distance from the shore, the treatment is more complex. This will be discussed in the next section.

The above equations, with minor variations in the determination of the required parameters, form the basis of the recommended short range models for routine releases by the following agencies: U.S. Nuclear Regulatory Commission (US NRC Reg. Guide 1.111, 1976); the Canadian National Working Group (NWG, 1982); the International Atomic Energy Agency (IAEA, 1980); American Nuclear Society (ANS, 1977); the Commission of the European Communities and National Radiological Protection Board (NRPB, 1982), NRPB (Clarke, 1979); Safety and Reliability Directorate (Fryer, 1978); Japan Atomic Energy Commission (AEC, 1965); Environmental Protection Agency (EPA, 1984); and Electric Power Research Institute (EPRI, 1982). A recent review (Moran et al., 1984) has recommended the Gaussian-model-based CDM (Climatological Dispersion Model) among the EPA-sonsored UNAMAP (User's Network for Applied Modelling of Air Pollution) models (EPA, 1984) for application to routine tritium releases from CANDU power

plants. Thus using the above equations as a basis for determining data requirements of short range models is justified.

There is a trend towards utilizing repeatedly the short-term form of the Gaussian equation (B.2) instead of the long-term form (B.1) since there is then a smooth transition from the dispersion characteristics of short duration releases to those of longer duration (Fryer, 1978). Also, this method is more useful for non-uniform releases in time. Use of this method is made increasingly easier by the availability of hourly on-site data, which are required for such repeated calculations.

A further modification that needs to be made to the above equations is to correct for the radioactive build-up and decay of various isotopes, and their removal from the plume by dry and wet deposition. These processes have been considered by CSA (1983), US NRC (Reg. Guide 1.111, 1976), IAEA (1980), and EPA (1984). Comprehensive descriptions for correcting the above equations for these phenomena are available in some recent reviews (Clarke and MacDonald, 1978; Jones, 1981; Rao, 1984; Ermak, 1977; Horst, 1977, 1984; EPRI, 1979). The more realistic surface depletion methods seem to be superior to source depletion methods. A detailed discussion of removal mechanisms is beyond the scope of this report and the reader is directed to the above references. For the purpose of identifying the necessary input parameters for these modifications, it is sufficient to note that the meteorological parameters required here are the hourly rate and form (rain, snow, etc.) of precipitation, from which the long-term amount, frequency, and duration of precipitation can be ascertained.

Guidance for the values of radionuclide dependent parameters such as dry deposition velocity and scavenging coefficient is also clearly outside the scope fo this study. They are considered in the CSA standards (CSA, 1982; 1983) and further information is available from Jones (1983), Brenlet and Vogt (1981), and Hales (1972).

The meteorological parameters required as direct input for Equations B.1 and B.2 are:

- hourly transport wind speed u at release height,
- hourly transport wind direction θ at release height, and
- mixed layer height h_i.

For calculating the effective source height H in the above equations, the required meteorological input parameters are (CSA, 1983, Appendix A):

- hourly transport wind speed u at release height,
- temperature of the ambient air T_a (°C), and
- vertical temperature gradient in the atmosphere $\frac{dT_a}{dz}$ (°C m^{-1}).

For obtaining Σ_y and Σ_z, the atmospheric dispersion parameters σ_y and σ_z are required. A detailed discussion of the various methods of obtaining these parameters from meteorological parameters is beyond the scope of the present report. A summary of the commonly used methods for obtaining σ_y and σ_z from meteorological parameters is given in Appendix A. Briefly, all these methods fall in one of three categories:

(i) methods that utilize a stability class for both σ_y and σ_z; once this stability class is determined using whatever means (e.g., STAR, temperature gradient, or horizontal wind direction standard deviation methods, see Appendix A), σ_y and σ_z are then determined from prescribed functions or graphs,

(ii) methods that utilize a direct measurement for only one of these parameters; most often σ_y; for σ_z, a stability class is first determined based on this measurement by whatever means, σ_z is then determined from prescribed functions or graphs,

(iii) methods that utilize direct measurements of meteorological parameters for both σ_y and σ_z.

For (i) and (ii), a detailed discussion of the various methods for determining stability class is beyond the scope of the present study. They are, however, mentioned in the Appendix as part of each individual method.

Theoretically, the methods that fall under (iii) will be the most desirable. However, in practice, methods for determining σ_z directly from measurements have not yet been widely accepted as discussed in Appendix A.

The second most desirable category is (ii). Among these, methods that utilize for the stability class a measurement that is independent of any measurements used for σ_y are preferred over methods that utilize the same measurement for both σ_y and the stability class.

The least desirable and yet the most commonly used category is the first category.

The following method, that falls in the second category for $u > 1.5\ m \cdot s^{-1}$, and that falls in the first category for $u < 1.5\ m \cdot s^{-1}$, is recommended by the present study:

(a) σ_y should be determined by formulae from measurements for the standard deviation of horizontal wind direction σ_θ, except when the wind speed is below $1.5\ m \cdot s^{-1}$ in which case it should be determined from prescribed functions or graphs via a stability classification that is determined from measurements of the vertical temperature gradient dT_a/dz.

(b) σ_z should be determined from prescribed functions or graphs via a stability classification that is determined from measurements of dT_a/dz.

The "prescribed functions or graphs" can be taken as those given by N288.2 (CSA, 1983, Section 2.4).

The meteorological input parameters required for the recommended method for determining σ_y and σ_z are:

- hourly standard deviation of horizontal wind direction σ_θ (rad),
- hourly vertical temperature gradient dT_a/dz ($°C \cdot m^{-1}$), and
- meteorological roughness length z_o(m).

For determining the deposition rate constants, the required meteorological input parameter is:

- hourly precipitation rate ($mm \cdot h^{-1}$) and form.

The short-term equation (B.2), together with its associated modifications to cover various phenomena, is also used for short range - simple terrain dispersion calculations for design postulated accidents and emergency conditions (CSA, 1982; USNRC Reg. Guides 1.3, 1.4, 1.145; NWG, 1982; IAEA, 1980; ANS, 1977; NRPB, 1982; Clarke, 1979; Fryer, 1978; Japan AEC, 1965; EPA, 1984; EPRI, 1982). The same parameters as above are required on an hourly basis from an on-site meteorological program. Of course, the data recording and analysis requirements will be different, especially for emergency conditions, when on-line access is required. These latter considerations will be addressed in Section 3 of this Chapter and Chapter D.

Under highly convective conditions that usually occur under strong insolation in spring and summer months, plumes from an elevated release within the mixed layer could be brought down at some distance from the release location, causing high short-term ground level concentrations. This may be especially important for emergency conditions. Such situations cannot be adequately modelled by any of the above methods and special techniques should be used. One such model that has been developed in Canada and used for continuous emissions from tall stacks of coal fired generating stations is that of Venkatram (1980), and Venkatram and Vet (1981). However, applicability of such convective boundary layer models to releases from nuclear generating stations, especially for use under emergency conditions, needs to be investigated. In any case, the input parameter requirements of this model are already covered by the above lists except for:

- the convective velocity scale, w_* ($m \cdot s^{-1}$), defined by: $(g\ Q_o h_i / T_a)^{1/3}$, where
  - g = gravitational acceleration, 9.81 $m \cdot s^{-2}$
  - Q_o = surface kinematic heat flux ($m \cdot K \cdot s^{-1}$)
  - h_i = height of mixed layer (m)
  - T_a = ambient temperature (K)

Q_o can be estimated from measurements of incoming solar radiation.

1.2 Short Range - Complex Terrain

In contrast to the multitude of well established methods for calculating dispersion over simple terrain, complex terrain models are relatively few and most are still under fundamental development (Egan, 1984). Apart from research grade numerical Eulerian models, there are two practical approaches:

- Lagrangian models,
- Algorithms based on modifications to the simple terrain Gaussian formulations (which are simple analytical Eulerian models).

Under "complex terrain," we shall look at three distinctly different types of terrain, for each of which separate models of the "Gaussian" type have been developed. These are:

- hilly terrain, consisting of isolated hills (as opposed to mountain ranges) whose heights may or may not exceed release heights,
- deep and long valleys, and
- coastal areas near large bodies of water.

Let us now briefly review the important considerations for pollutant dispersion over these terrain types.

Hilly Terrain

If an isolated hill is near an elevated source, the plume may rise over the hill, go around the sides, or impinge on the hill, depending upon release height and atmospheric stability. If a rise in terrain is downwind of a source in neutral and unstable conditions, the plume tends to ride up the slope while losing part of its effective stack height H relative to the ground. Based on potential flow theory and wind tunnel experiments, the reduction is usually taken as the terrain height h_t or $H/2$, whichever is smaller (Hanna et al., 1982, see Figure B.1). In stable conditions, it is usually assumed that the plume maintains a constant elevation and the effective plume height H is reduced by terrain height h_t. Thus if the terrain height is greater than the effective plume height, the plume may impinge on it under stable conditions. Plume impingement may be modelled by using image sources similar to the limited mixing Gaussian models of the previous section. However, in the case of a sudden terrain rise this will lead to increases of concentration within the plume, which is contrary to second law of thermodynamics. In the model, axial concentrations are limited to the maximum concentration before impact.

The UNAMAP models (EPA, 1984), such as CRSTER, ISC, MPTER, MSDM, and VALLEY, which have terrain corrective algorithms, all utilize the above described algorithm or minor variations of it.

A more recent algorithm which is still under development (Egan, 1984) is based on the calculation of the height of a critical streamline. The part of the plume that is above this streamline at the impact point, called the "lift"

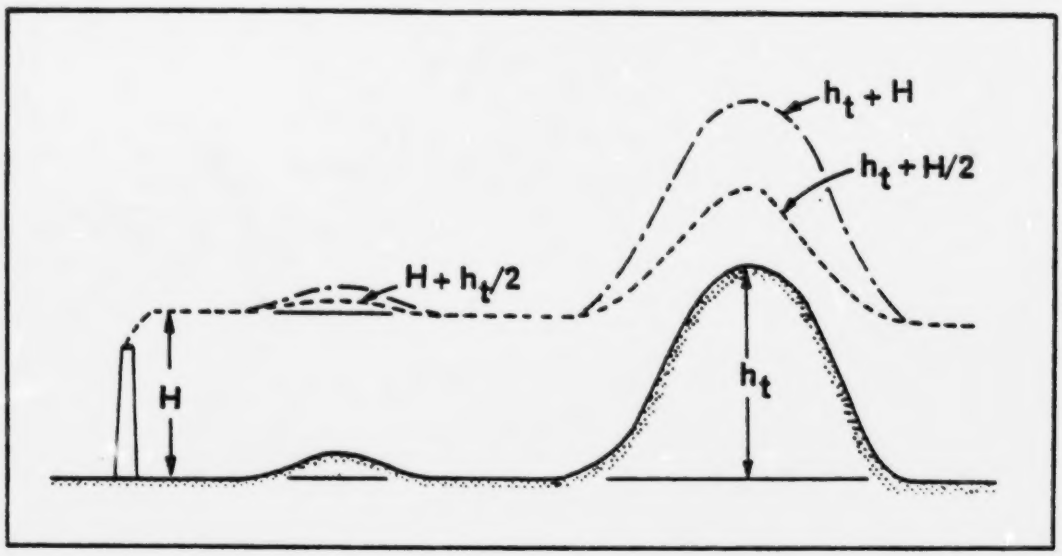

Figure B.1 Illustration of plume height assumptions for neutral and unstable conditions. (Adapted from Hanna et al., 1982)

component, is allowed to go above the hill, and the part that is below the streamline, called the "wrap" component, is forced to go around the hill. Analytical expressions based on the familiar Gaussian formulae are prescribed for these two components. Further discussion of this model is not considered appropriate at this time, considering that it is still under development.

For the purposes of including an algorithm for hilly terrain within the CSA (1983) framework, it is recommended that the former algorithm, which is presently the basis of the EPA recommended models, be utilized. For normal operation, the algorithm can be used both in short-term (i.e., repeatedly for each hour) or long-term (i.e., for each weather category) modes as described in the previous section. For design postulated accidents and emergency conditions it should be used in the short or long-term mode depending on duration of release. The meteorological parameters identified in the previous section are sufficient for inputs to this algorithm.

If there is a terrain rise upwind of the source and the average slope of the rise above the source exceeds 2% (Figure B.2), downwash may be induced by the air flowing over the terrain top (Hanna et al., 1982). For steep hills, it is possible to get a "cavity" effect, similar to the wakes behind buildings (Figure B.2). This cavity would extend three to ten hill heights downwind, which would possibly cause downwash and fumigation of a plume in this region. It is recommended that the characteristics of such sites be determined by field or laboratory experiments before any modelling is attempted (see Section 4 of this Chapter).

Valleys

In case of deep, long valleys, a night-time drainage layer may form at the sides and the bottom. Pollutants emitted near the slopes within the valley would be trapped within this drainage layer and transported down the valley, regardless of the general synoptic flow pattern in the area. Also, pollutants emitted at an elevation below the valley depth may be trapped at this height and distributed horizontally within a thin layer across the valley. Thus, high concentrations may be observed at the sides of the valley at locations where this layer intersects the slopes. These pollutants may then be brought down the slopes by the drainage flow. In the morning, break-up fumigation may bring the pollutants within the thin horizontal layer down to the valley floor, when the stable layer below this pollutant layer is eroded from below by the heating of the ground. For inclusion within the framework of CSA (1983), it is recommended that the model described by Briggs (1979) be utilized for drainage layers, and the model developed by Whiteman (1983) be utilized for break-up fumigation conditions. The meteorological parameters identified in the previous section are generally sufficient as model inputs. However, site characterization based on field or laboratory experiments is recommended before any site-specific modelling is attempted.

Coastal Areas

Pollutant transport and diffusion in coastal regions is of particular interest to the nuclear industry in Canada since most existing power plants are in such regions. Hence a more detailed, discussion will be provided here relative to other types of terrain discussed above. At the interface of any two zones of

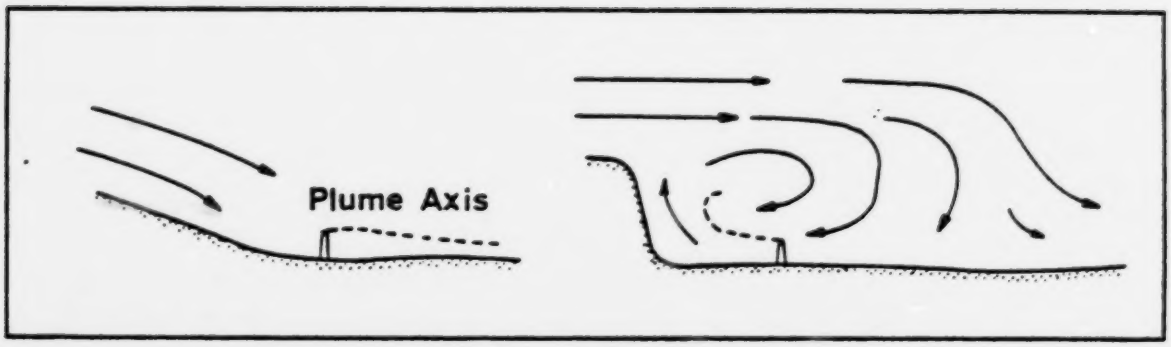

Figure B.2 Effect of upwind terrain on plume trajectories for gentle slopes and abrupt ridges. (Adapted from Hanna et al., 1982)

different stabilities or roughness characteristics, an internal boundary layer will develop over the downwind zone reflecting the characteristics of this new zone. In coastal regions, the land/sea (or lake) interface poses particular problems to the dispersion modeller. A series of papers by Portelli (1982), Kerman et al. (1982), Hoff et al. (1982) and Anlauf et al. (1982) describes a major experiment on coastal diffusion processes carried out at Nanticoke, Ontario.

During off-shore flow, if the release is somewhat inland from the shore, dispersion during the passage over land can be estimated using the methods described before (Jones, 1983). Over water, however, there are vast differences in the boundary layer structure relative to the boundary layers over land, and specially developed dispersion parameters should be used (Hanna et al., 1984). One consolation is that the water surface is relatively flat and the Gaussian equation corresponding to the simple terrain case can be used. The required input parameters are the same as before except that they must now be determined over water, and characteristic sets of seasonal and diurnal values of sea/lake and land surface temperatures would need to be determined during a site survey.

During winds that are parallel to the coast no special effect of the shoreline need be considered if the plume travel is only over land. If the shoreline changes direction several times, multiple changes of the underlying surface need also be treated (Hanna et al., 1984; Jones, 1983).

At the land/sea interface, where stabilities and turbulence intensities may change significantly, the new dispersion rates can be accounted for by means of a virtual source. The change does not take place until the plume intercepts the rising internal boundary layer h_T.

Let us now consider a case of particular interest where there is on-shore flow, which could be due to gradient wind or due to sea/lake breeze effects (Merry and Currier, 1981). The dispersive characteristics of the flow will be dependent on if the water is warmer or colder than land.

If the water is warmer than land, such as in fall and winter, and likely coinciding with stable conditions over land, the methods described earlier for estimating dispersion over simple or complex terrain can be used (Jones, 1983).

If the water is colder than land, corresponding to stable conditions over water and unstable conditions over land, such as in spring and summer, again the methods described earlier can be used for releases within the internal boundary layer, except that the mixing layer height h should be replaced by the internal boundary layer height h_T. Clearly, the magnitude of h_T is important even for deciding which model to use. The growth of h_T has been considered in N288.2 (CSA, 1983). Several other models are also available (Raynor et al., 1979; Venkatram, 1977; Hanna et al., 1974). According to Misra and Onlock (1982), h_T is proportional to the square root of the distance from the shore, the constant of proportionality being between 2 to 6. Most elevated releases from a CANDU power plant are expected to take place within 1/2 km of the shore and at a release height of ~ 50 m through short stacks, which could result in

the entrainment of the plume in the wake of the reactor building. However, if we disregard this building wake effect, it is likely that plumes could rise high enough to allow travel some distance within the stable layer above the newly developing internal boundary layer. The pollutants can thus travel considerable distances within the stable layer until the plume meets the internal boundary layer and fumigated down to ground level. The models due to Deardorf and Willis (1982) or Misra (1980) may be used in these cases. The latter model has been used extensively for shoreline diffusion problems at the north shore of Lake Erie (Misra and Onlock, 1982). It can be used within the framework of N288.2 (CSA, 1983). The meteorological parameters identified so far are sufficient for determining the required inputs to this model.

If the on-shore breeze is due to a sea/lake breeze effect, as opposed to a gradient wind, a further complication arises due to the circulation pattern established over the coastal region. Sea/lake breezes occur on days when strong thermal convection occurs and the gradient wind is light. If the gradient wind is strong and against the sea/lake breeze direction then a sea/lake breeze cannot occur. A sea/lake breeze is accompanied by a front, which marks the extent of the sea/lake breeze penetration, at a distance between a few kilometers up to tens of kilometers from the shore depending on the sea-land temperature difference. A return flow aloft is also present (See Jones, 1983, for a more specific discussion of the methods for estimating these flows).

A pollutant emitted into the on-shore lake breeze may then be brought back with the return flow aloft. Also, since the sea/lake breeze direction would change diurnally, a pollutant emitted into the off-shore flow during the night might be brought back to the shore near the surface during the day. If a light gradient wind exists parallel to the shore persisting for a few days, a parcel of pollutant emitted into the sea/lake breeze may travel following a helical trajectory along the coast.

Sea/lake breezes are considered to be meso-scale phenomena, with spatial scales of a few to several hundred kilometers. Clearly, these medium-range phenomena significantly affect the short-range (<100 km) dispersion in a coastal zone. Hence, site characterization studies for determining, for example, mixing layer heights, should consider these larger spatial scales as well as the short-range.

Lagrangian Models

The above discussion of complex terrain features and models for estimating dispersion in the short-range have largely focused on Gaussian based analytical formulations. In the discussion on dispersion in coastal zones, the usefulness of calculating the trajectory of a pollutant has been pointed out. Calculation of trajectories take us into the realm of Lagrangian transport models.

Lagrangian models (e.g., Daggupaty, 1982; Schorling, 1984; US NRC Reg. Guide 1.111, 1976) in general are capable of treating different types of terrain without altering the fundamental approach to their treatment of transport, diffusion, and removal processes, and are equally applicable to simple terrain.

We shall now briefly describe the fundamental equations of these models for the purpose of identifying their required meteorological input parameters.

The location of a parcel of pollutant x at time $t = T_o + \Delta T$ is

$$x = x_o + \int_{T_o}^{T_o+\Delta T} \vec{u}\, dt, \qquad (B.3)$$

where x_o is the location at $t=T_o$, and $\vec{u}$ is the average three dimensional transport wind within the time step ΔT. Clearly, the magnitude of ΔT determines the spatial resolution of the model. Practically, however, the selection of ΔT is limited by the resolution of the available wind field both spatially and temporally.

Over simple terrain, a resolution of 100 km may be sufficient for trajectory calculations. However, over complex terrain, depending on the scale of topographical features, the required resolution may be as small as a few kilometers or less. For example, in order to determine if a certain parcel of pollutant would go above or around a 500 m isolated hill, a wind field resolution of a few tens of meters may be required. Clearly, such resolutions require research grade Eulerian dynamic wind field models, and in that case it is better to utilize Eulerian transport models rather than the simpler Lagrangian transport models. Since Eulerian models are not generally practical or available, such situations are best treated using the analytical approaches already described, and Lagrangian models are best used for tracking the general position of a parcel in the horizontal using horizontal wind fields, which are generally available within a resolution of a few hundred kilometers over most of North America. With dynamic wind field modelling or special tower networks, it is possible to increase the resolution to less than 100 km, in which case short- to medium-range trajectory calculations can be made.

The ground level ($z = o$) concentration distribution within an expanding parcel can be estimated using the Gaussian puff formulation (Daggupaty, 1982):

$$C_{\text{short term}} = \frac{2\,Q}{(2\pi)^{3/2}\,\Sigma_x\,\Sigma_y\,\Sigma_z}\,\exp\left\{-\frac{1}{2}\left[\left(\frac{x-ut}{\Sigma_x}\right)^2+\left(\frac{y}{\Sigma_y}\right)^2\right]\right\} f(\Sigma_z,\, H,\, h_i) \qquad (B.4)$$

The location of the parcel is estimated using equation (B.3). It is difficult to handle all of the special cases such as limited mixing, fumigation, build-up, decay and removal, but they can be treated using methods already considered, taking into account changing conditions with each time step.

For repeated releases, separate trajectories need be calculated for each release, and the contributions to a receptor from each puff summed up in time. For continuous releases, plume segments can be used instead of the puffs, each segment changing direction in each time step.

The input parameters required are basically the same as those identified so far, except that they are now required at the location of the parcel at the

beginning and end of each time step. Different Lagrangian model formulations may require slightly different sets of input parameters. However the density of observing stations is invariably insufficient to provide wind fields that would make these models useful in the short to medium ranges unless wind fields can be obtained from a dynamic model.

1.3 Medium to Long Range

The Lagrangian models considered in the previous section are perhaps more applicable to medium to long ranges (from 100 to a few thousand km) than to short range, as should be evident from the discussion regarding the resolution of the available wind fields. The principles of applying the Lagrangian models to the longer ranges are the same as discussed before. Most recent long range models are specifically designed for releases from coal-fired power plants rather than releases from nuclear power plants although they can readily be modified for radioactive releases. A comprehensive review of currently available Lagrangian models has recently been completed by Fung et al. (1985) and based on the results of a rigorous evaluation, the model with the best physics is presently being implemented by Concord. A recent model developed specifically for the long range transport of radionuclides has been reported by ApSimon et al. (1985). Lagrangian models are more suitable for episodes of short duration rather than long term releases, due to running costs.

Two other types of models for long range applications are the Eulerian "grid" and "statistical" models. "Grid" models require numerical solution of three-dimensional partial differential equations and are still in their fundamental development stage. "Statistical" models are very similar in nature to the long term Gaussian equation B.1. They are solutions to various simplified forms of the general transport equation (the Gaussian equation is also a solution to this general equation). Available "statistical" long range transport models are generally designed for sulphur dioxide emissions from coal-fired generating stations and not for radioactive releases. They have a resolution of about 100 km. Since they are more suitable for long term releases rather than episodic releases, they can be modified for application to releases during normal operation of CANDU power plants if long range transport of such releases is of interest. Modification would consist of first an examination of model assumptions and parameterizations for applicability to the radioactive species of interest, and then implementation of the required parameterizations for these species. Validation of such a model would require long term emission inventories for the region of interest (e.g., northeastern North America) and longterm concentration and deposition data in the same region. Concord has recently completed a comprehensive survey of available "statistical" long range transport models (Alp et al., 1985), and implemented and applied the state-of-the-art model for long range transport problems in Canada.

2. Summary of Meteorological Input Parameters Required for Dispersion Calculations

Throughout Section 1 of this Chapter, the meteorological input parameters required for dispersion calculations for short and long range, and simple and complex terrain, have been identified. These are now summarized below:

- hourly transport wind speed $u(m \cdot s^{-1})$, and direction θ(radians), at release height,
- standard deviation of the horizontal wind direction σ_θ (radians),
- mixed layer height h_i (m),
- temperature of the ambient air T_a (°C),
- the vertical temperature gradient dT_a/dz (°C m^{-1}),
- meteorological roughness length z_o (cm),
- hourly precipitation rate $(mm \cdot h^{-1})$,
- convective velocity scale w_* $(m \cdot s^{-1})$.

The above listed "parameters" are required for the dispersion calculation methods applied to normal operation, design postulated accidents, and emergency conditions. The specific data requirements for thee three "conditions" will now be addressed in the following section.

We shall then discuss some aspects of site characterization that would be needed before finalizing on-site meteorological programs and attempting any site-specific dispersion modelling.

The meteorological "measurements" required for obtaining the "parameters" listed above will be described in Chapter C.

3. Specific Requirements for the Three "Conditions"

3.1 Normal Operating Conditions

This condition may be looked at from two perspectives. Firstly, for a site safety analysis report, data will be required representative of all meteorological conditions likely to occur at the site. A reliable climatological analysis would require over 10 years of data. ANS (1984) recommend that 5 or more years of data from nearby representative stations be used for preliminary evaluations. Care should be taken in selecting a representative station especially for coastal sites where the nearest station may not be the most representative. Where a nearby representative station capable of providing the measurements that will be specified in detail in Chapter C cannot be found, on-site tower-based measurements are recommended.

For on-site data, the absolute minimum amount of data taken to be representative would be a full year of measurements although ANS (1984) stress 2 or more is preferable. The basic data should be reduced to hourly average values. For normal operating conditions representative hourly concentrations can then be calculated for at least one complete year.

From the second perspective, the data requirements during actual operation would be different. In this case, real time data and forecasts would be desirable for controlled intermittent releases.

3.2 Design Postulated Accidents

The required input data for design postulated accidents are those which will produce "realistic conservative" dispersion conditions. A recent Concord study for AECB (Alp et al., 1985) has indicated that for releases of 10 hours or more duration, at least five years' data would be needed for representative statistics on concentrations. From the hourly data, frequency of occurrence of possible concentrations at given distances and directions and risk to populations can be calculated (US NRC Reg.Guide 1.145, 1983; IAEA, 1980).

The above implies that, for normal operating conditions and design postulated accidents, a permanent tower-based measuring system is not required, provided that an adequate historical data base has been established from on-site programs.

3.3 Emergency Conditions

Real-time and forecast data are required for model input during emergency conditions. Following the accident at Three Mile Island the capability of being able to interrogate the meteorological systems remotely became apparent (US NRC Reg.Guide 1.23, 1980). The real-time data should be available on-line simultaneously in the control room, at an emergency control centre and at a designated Atmospheric Environment Service (AES) facility capable of providing weather forecasts. The format used should be established through discussion between AECB and AES. There should also be remote access to data bases of 15-minute averages of meteorological parameters for at least the previous 12-hour period (US NRC Reg.Guide 1.23, 1980) for accurate forecasting purposes. Under emergency conditions forecasts of the wind speed and direction at the release height, stability class and mixing height would be immediately required.

Also, close liaison between the facility and the nearest primary forecast weather office (a list of these can be found in AES, 1977), and familiarity of the AES staff with the micrometeorology of the site as it relates to atmospheric dispersion are essential.

The above implies that, for emergency conditions, a permanent tower-based measuring system will be required on-site.

4. Field Study Requirements for Site Characterization

For sites that are on complex terrain such as hills, valleys, and coastal sites, site characterization studies are recommended prior to finalizing on-site meteorological programs, and selecting site- specific modelling requirements. In the following discussion, we shall be guided by the list of parameters given in the previous section. The discussion is by no means exhaustive, but attempts to point out significant need areas only.

- The meteorological roughness length that is needed in specifying the diffusion parameters should be estimated for each compass sector within a 100 km radius of the nuclear facility. A survey of land use in the vicinity of the facility is sufficient for this purpose (Chapter C, Section 6). If this roughness changes with distance and time through urban development, forestation, etc., then the roughness lengths should be updated.

- Before deciding on the location of a meteorological tower that would be used for measuring temperature gradient, typical mixing heights at that location should be determined so that the upper and lower measurements are both in the same layer for which stability characteristics are being sought. This is especially important for coastal sites where a relatively thin internal boundary layer may be present. This will be discussed further in subsequent sections.

- The depth of penetration of a sea/lake breeze and its typical diurnal variations in terms of its speed and direction should be determined for a given site. Once these characteristics are determined, frequency of occurrence of these need also be known for safety analyses.

- The conditions under which convective boundary layer modelling need be applied and their frequency of occurrence for a specific site should be determined.

- In valley sites, height of typical inversion layers within the valley, and the thickness of and speed within the drainage layers need be determined as part of site characterization.

- In sites with surrounding hills, the downwash and "cavity" effects behind these hills, together with their frequency of occurrences need be determined.

- The density of wind speed measurements required to specify the wind field for dispersion calculations should be established for each site based on topography.

- Dispersion experiments should be carried out to establish the relationship between turbulence and diffusion at each site or, at least at a shoreline location typical of Canadian reactors. As recommended by NWG (1982), the recommended methods for calculating σ_y and σ_z should be tested and, if necessary, corrections to the formulae, stability classification schemes and conventional sigma curves should be made. Where meteorological conditions are dominated by sea breeze circulations it may be necessary to evaluate the turbulence typing schemes and curves in both the internal boundary layer and in the stable layer aloft.

C. METEOROLOGICAL MEASUREMENTS REQUIRED TO CALCULATE THE INPUT PARAMETERS

Methods by which the meteorological input parameters summarised in Chapter B, Section 2 may be obtained from raw meteorological data will be considered here.

1. Average Transport Wind

Wind speed and direction should be measured at two levels: 10 m, the standard synoptic observing height, and at the effective release height (50 m) (IAEA, 1980; ANS, 1984; and NWG, 1982). Although the wind speed at the effective source height, averaged over the required time-scale, is sufficient for input into the simpler models, use of the 10 m wind gives a more conservative esti-

mate of the concentration and measurement at two levels will allow a layer average wind speed to be calculated if necessary.

2. Standard Deviation of the Horizontal Wind Direction

The standard deviation of the horizontal wind direction should be measured at the two wind speed and direction measurement levels. A layer average can then be used to characterize the wind fluctuations for dispersion.

3. Mixed Laver Height, h_i

The mixing layer may be defined, for present purposes, as that layer of the lower atmosphere in which free vertical plume rise and growth is possible. The depth of the layer is called the mixing height, h_i. Determination of h_i on a routine basis using conventional instruments is difficult and requires vertical soundings using balloons or aircraft which are limited in space and time. Research into the use of remote sensing devices such as SODAR (sound detection and ranging) and LIDAR (light detection and ranging) for measuring h_i, and other diffusion parameters is at a fairly advanced stage and they are beginning to be used on a routine basis. A big advantage of remote sensing instruments is their capability of obtaining, from the ground, information that is highly detailed in space and time (Johnson and Ruff, 1976; Hoffnagle et al., 1981).

For present purposes mixing height soundings for the site should be conducted during the site survey using an acoustic sounder, ideally covering all seasons. This will allow an estimate of h_i to be made taking into account the prevailing meteorological conditions, season and time of day. Consideration should also be given to maintaining an acoustic sounder that could be made readily available for use during emergency situations. The use of an acoustic sounder on a continuous basis is not recommended at this time; however, if and when the use of remote sensing devices becomes established on a routine basis, this recommendation will need to be reviewed.

The input value of h_i will depend on the "condition" being considered. For long term, routine releases a climatological average of the mixing height relevant to the season and time of release obtained from data acquired during the site survey would be required. Alternatively, mixing height values may be interpolated from tables of maximum (afternoon) mixing heights (Portelli, 1977) and an estimated (from site survey data, or, if not available, from Clarke et al. (1984) who suggest a minimum mixing height value of the order of 100 m for rural areas) minimum mixing height. A linear (with time) interpolation may be used between sunrise (minimum) and mid-afternoon (maximum)(Portelli, 1985). A more complex interpolation technique is given by Demerjian and Schere (1979). For design-postulated accidents a value of h_i corresponding to "worst case" conditions is necessary while an emergency situation would require a real-time value of h_i.

4. Ambient Air Temperature

Knowledge of the ambient air temperature is required to calculate the air density. Measurement should be made at the 10 m level.

5. Vertical Temperature Gradient

Measurements of temperature at the 10 and 50 m levels are required for the vertical temperature gradient, which is approximated by $\Delta T_a / \Delta z$.

6. Roughness Length, z_o

The meteorological roughness length, z_o, can be defined as the height at which the neutral wind speed profile extrapolates to zero. The value of z_o depends on the nature of the surrounding terrain and wind direction. z_o may be determined from wind speed profile data or can be estimated from a description of the surrounding surface features (see Figure B.3). As dispersion models are not very sensitive to z_o (Hoffnagle et al., 1981), an estimate should be sufficient.

If the surrounding roughness elements are non-homogeneous with respect to wind direction then values should be estimated for each relevant compass sector. Account should also be taken of seasonal changes which may occur due to tree growth and snow cover.

Derivation of z_o from wind speed profile data would only be relevant if the terrain around the site is relatively flat and homogeneous. In this case Hoffnagle et al. recommend that wind measurements be made at three heights between 2 and 20 m, with 5% wind speed accuracy, 10s response time, 30s sample averaging time, and 1h sampling duration.

7. Precipitation

Precipitation passing through the effluent cloud or plume will collect particulates or scavenge soluble gases or vapours. This will deplete the plume. A washout coefficient is included in the models which is a function of precipitation rate, precipitation drop or particle size spectrum, radioactive particle size distribution and solubility of the effluent in water. The washout coefficient may be obtained from charts, for example IAEA (1980), as a function of rainfall rate. However, rainfall or rainfall rate is very rarely uniform and correction should be made only for those areas where precipitation has actually occurred. Since the washout coefficients are imprecise and of the most important radionuclides only iodine is subject to significant wet deposition, an accurate on-site precipitation rate measurement is not required. It is recommended that the precipitation rate at site be estimated from rates measured by gauges within the national observation network or radar in the surrounding area (NWG, 1982). The validity of this recommendation will obviously depend on the proximity of the alternative source of data to the site. If precipitation is measured on-site, measurement of the hourly rainfall amount would be sufficient.

8. Convective Velocity Scale

As discussed in Chapter B, Section 1.1, under highly convective conditions the use of a convective boundary layer model could be considered, if investigation proves their applicability to releases from nuclear generating stations.

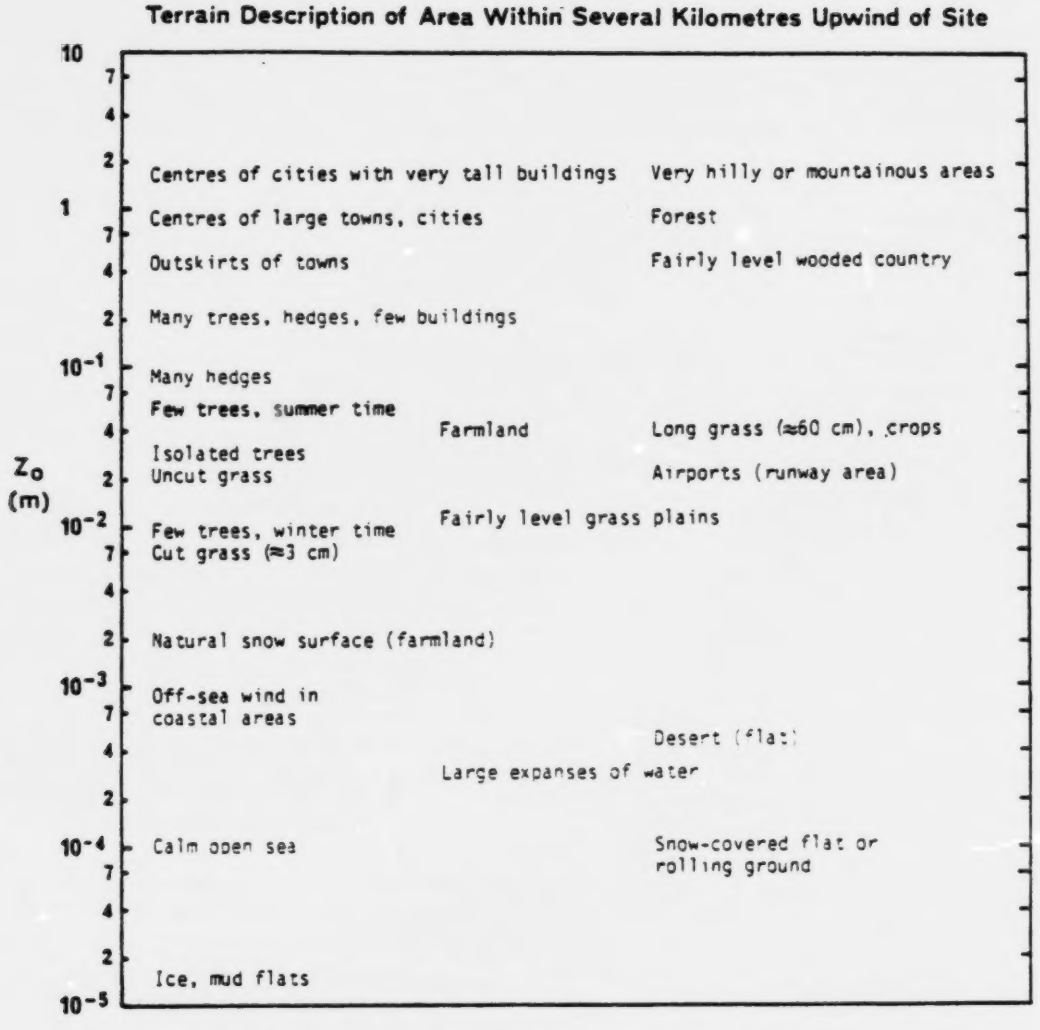

Figure B.3 Estimation of z_o from surrounding surface features. (After ESDU, 1972)

These models require an estimate of the convective velocity scale,

$$w_* = (g\, Q_o\, h_i / T_a)^{1/3}$$

as defined in Chapter B, Section 1.1.

As w_* depends on the 1/3 power of Q_o and h_i, an estimate of w_* should be relatively insensitive to errors in Q_o and h_i. Q_o depends mostly on the incoming solar radiation and the nature of the surface. Briggs (1975) gives a method to estimate Q_o directly from a measure of the incoming solar radiation (See also Venkatram, 1981). A value of solar radiation obtained from a climatologically representative synoptic station should be sufficient on most occasions. The main criteria for judging climatological representativeness are the proximity to the site and similarity of location relative to the surrounding terrain. For example, Trenton Airport, due to its lakeside location, would be more representative of conditions at Pickering than Toronto International Airport even though the latter is much closer to the site. Meteorological records obtained during the site survey should be compared for all seasons and time of day when selecting a representative station(s). However, for real-time usage, the judgement of a professional meteorologist should be sought as under certain meteorological conditions (e.g., during a frontal passage) the values from the "designated" station may not be valid. If the convective boundary layer model is to be used extensively consideration should be given to maintaining a pyranometer on site for use during emergency conditions.

D. ESTABLISHING A METEOROLOGICAL MONITORING SYSTEM

1. Siting of the Meteorological Towers

The purpose of on-site meteorological instrumentation is to characterize the atmospheric dispersion in the vicinity of the site during an effluent release. The range at which these measurements will remain relevant will depend on the surrounding topography and the actual meteorological conditions. Ideally, before deciding on the siting of a tower or towers, a site survey should be carried out to determine such information as prevailing wind direction, typical mixing heights and possible disturbances to the airflow caused by topography.

The following are some general recommendations for the siting of a primary tower (US NRC, 1980):

(1) The meteorological tower site should represent as closely as possible the same meteorological characteristics as the region into which any airborne materials will be released.

(2) Wherever possible, the base of the tower or mast should be sited at approximately the same elevation as the finished plant grade.

(3) The tower should be located in an area where singular natural or man-made obstructions or the heat dissipation system to be used during plant operation will have little or no influence on the meteorological

measurements. Locating the tower or mast directly downwind of such obstructions or heat outlets under prevailing wind downwind conditions should be avoided.

(4) The height of natural or man-made obstructions to air movement should, ideally, be lower than the measuring level to a horizontal distance of 10 times the measuring level height.

On the final point it is also recommended that the base of the tower be no nearer than the greater of either 20 tower or 20 obstacle heights to the nearest obstacles to the flow, NWG (1982).

Once a tower has been sited the terrain around the base of the tower should be kept clear of ground cover or tree growth which may obstruct the airflow in the vicinity of the instrumentation system and result in erroneous measurements.

The additional factors which need to be considered to adequately represent the meteorological conditions at coastal and other more complex sites are discussed in the following section.

1.1 Siting of Towers in Complex Terrain

The emphasis in this section will be on sites at coastal locations as most of Canada's existing nuclear facilities are in such locations. The several meteorological differences between coastal and inland sites such as land and sea/lake breezes, less intense radiative cooling by night and convective heating by day, are caused primarily by the thermal and frictional discontinuity that exists between the land and water surfaces during onshore and offshore flow. An internal boundary layer in the downwind direction is established during on-shore or off-shore flows. The slope and height of this layer vary with temperature difference between, and roughness of, the two surfaces, wind speed, cloudiness, season and time of day. Conditions will differ within, upwind of, and above, this boundary layer. Lapse rates may change from very unstable to very stable on crossing from the lower mixed layer to the unmodified air above. A critical error could, therefore, be made if the boundary layer intersects the two measuring levels on the meteorological tower (Figure D.1). For a discussion of probable prediction errors which could occur under these conditions during onshore flow see Raynor et al. (1980).

Unless the site is located such that there is a land mass affected during offshore flow, for example a river estuary, the flow inland will be of most concern. It is, therefore, essential that the primary tower is located such that the upper measuring level is always below the minimum internal boundary layer height during onshore flow. Should this not be possible due, for example, to elevated releases from a plant nearer to the coast, then an additional instrumentation level below the minimum internal boundary layer height should be added to the tower to characterize the mixed layer but should be used only when necessary.

Further consideration of the internal boundary layer is given in Chapter B, Section 1.2 but it is essential that knowledge of the local variations in boundary layer heights derived from experiments or computational models are taken into account before the tower site is chosen.

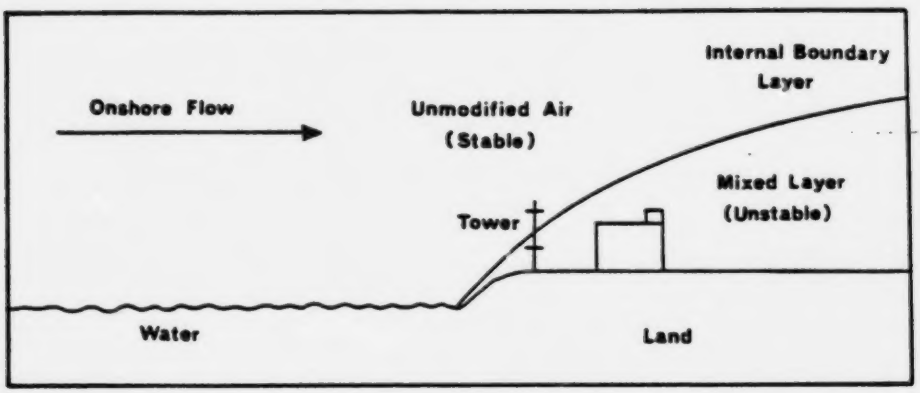

Figure D.1 Example of the intersection of the internal boundary layer by a poorly sited tower during summertime onshore flow.

If the plant is closer to the coast than the tower and it is possible that the releases may be made into the stable, unmodified air above the boundary layer, then measurements in the unmodified air are necessary to calculate diffusion and passive fumigation when the plume enters the boundary layer (Raynor et al., 1980). A secondary tower is, therefore, necessary to determine conditions representative of the unmodified air. This could be at the shoreline or on the water itself. Where consideration of offshore flow conditions is also necessary, similar principles apply, i.e., a secondary tower is necessary to characterize conditions over the water below the internal boundary layer. This tower may be located either on the water itself or on the opposite shoreline. The possible options available are illustrated in Figures D.2 and D.3 (adapted from Raynor et al., 1980). If the water is shallow enough to allow the fixing of a tower in the water itself, then one tower may serve both on and offshore conditions (Figure D.2). However, the tower must be situated on sufficient distance from either shore such that it will always be within the over-water internal boundary layer. Estimates of this distance could vary from several hundred meters to about two kilometers as may be obtained from relationships between the height of the boundary layer and distance from shore such as those discussed in Chapter B, Section 1.2 and by Raynor (1980). For deep water, or a shallow body of water which is too narrow to allow just one tower to be used but wide enough that the over-water internal boundary layer is of concern, then two secondary towers, one on each shoreline would be necessary to characterize the over-water internal boundary layer in both on and offshore conditions (Figure D.3).

The instrument heights on secondary towers should be chosen to give measurements representative of conditions within the boundary layer over the water while maintaining adequate separation between levels (Raynor et al., 1980). For the lower level, a height of 10 m over or at the edge of a large body of water (high enough for the temperature sensor to be clear of spray during high winds) or 5 m for smaller bays, estuaries or lakes, and a separation of 20 m or great enough such that likely differences in the quantities being measured are greater than the uncertainty in the measurements.

Hills, valleys, large structures or other obstacles in the site vicinity also require that additional thought be given to the tower location and the possible requirement for secondary towers.

In irregular terrain the mean atmospheric flow can be divided into two regimes (IAEA, 1976):

(1) A lower regime where winds are locally affected by the presence of the irregular terrain.

(2) An upper regime where winds are not so affected.

Where diffusion is likely to take place from one regime to the other it is necessary that measurements be made in both regimes as wind speed and direction and stability are likely to differ between the two.

At a valley site the primary meteorological tower should be located so that meteorological measurements are representative of conditions at the potential points of release. All levels at which measurements are made should be within

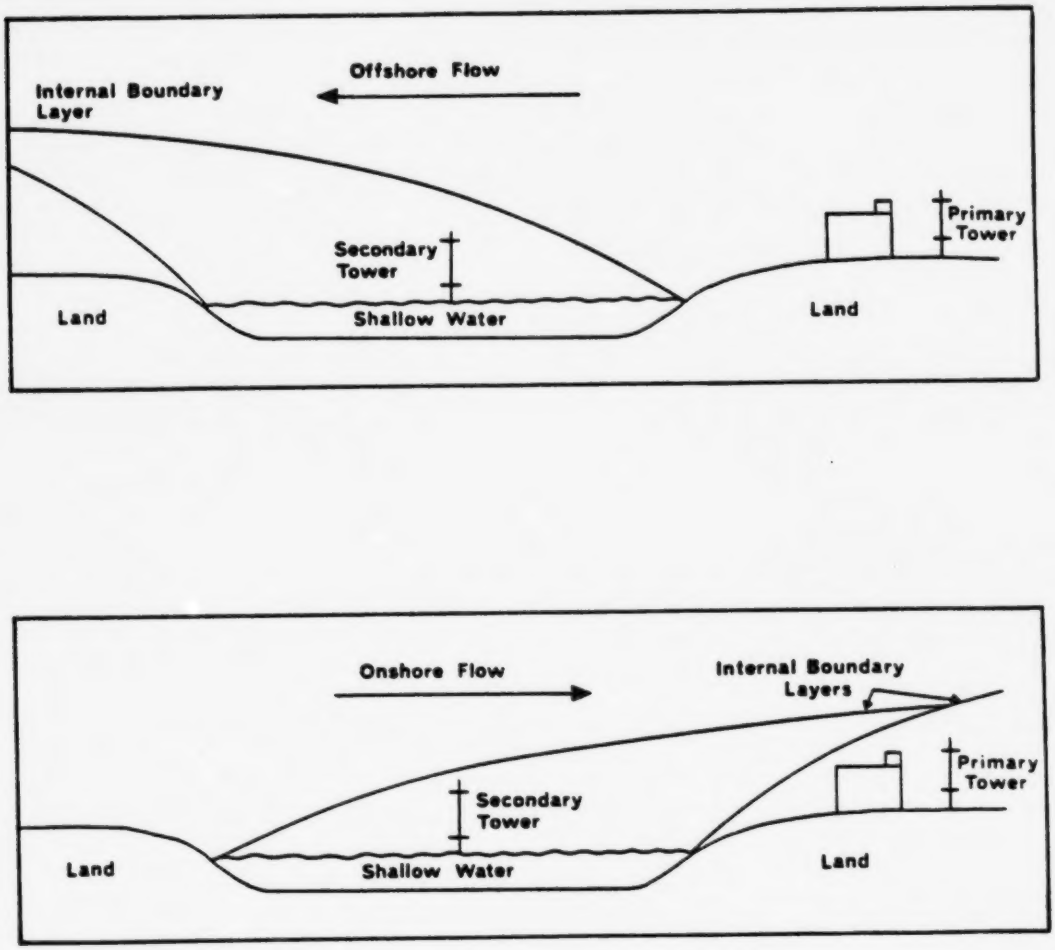

Figure D.2 Example of internal boundary layers and possible tower sitings for a shallow water, complex coastal location for (a) Offshore Flow and (b) Onshore Flow. (adapted from Raynor et al., 1980)

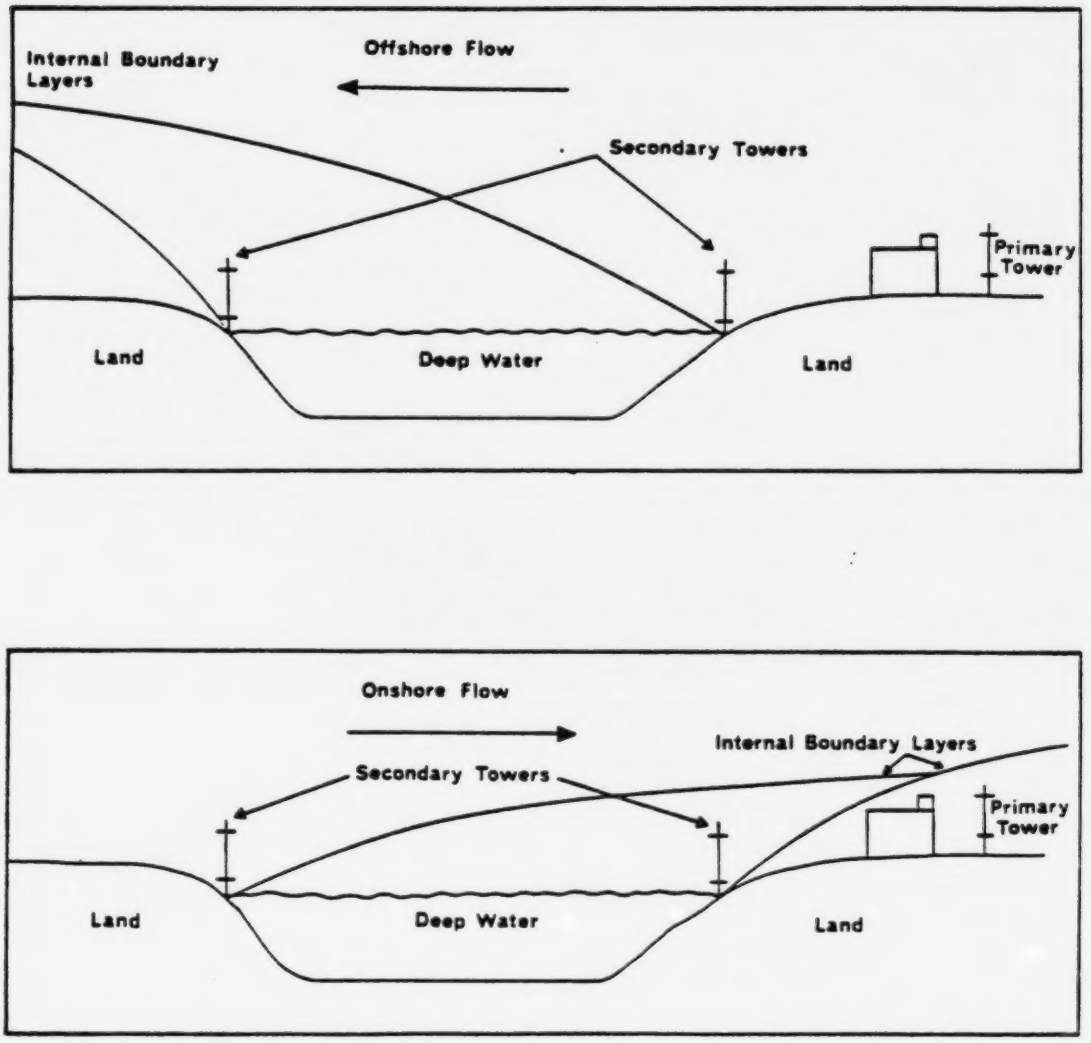

Figure D.3 Example of internal boundary layers and possible tower sitings for a deep water, complex coastal location for (a) Offshore Flow and (b) Onshore Flow. (adapted from Raynor et al., 1980)

the same thermal boundary layer (US NRC, 1980). Site experiments will again be necessary to determine drainage conditions and inversion depths before the tower site is chosen. A secondary tower should be placed outside the valley to characterize the upper regime.

Sites with more complex terrain will need to be considered on an individual basis to determine the siting and necessity of additional secondary towers.

2. Instrumentation

This section considers the instrumentation necessary for measurement of the required meteorological elements. Specifications will be given for system accuracy and performance. It should be noted that for a system, the accuracy of the final output value refers to the composite accuracy of the whole system. Individual errors may be introduced by each component of the system; sensor, cables, signal conditioner, ambient environmental conditions for signal conditioning, recorders, data reduction system. The system accuracy is determined by the root sum of the squares (RSS) method considering each of these individual errors (US NRC, 1980).

The system accuracy specifications given here are based on general experience of researchers and available technology. Ideally, however, they should be based on error propagation analyses (for example, Kline and McClintock, 1953) as determined by desired or achievable accuracy limits on model predictions. This error propagation analysis is now briefly described. For a specified desired result R, that can be calculated as a function of n measured variables v_i with given uncertainties w_i, the overall uncertainty w_R can be calculated by

$$w_R^2 = \left(\frac{\partial R}{\partial v_1} w_1\right)^2 + \left(\frac{\partial R}{\partial v_2} w_2\right)^2 + ... + \left(\frac{\partial R}{\partial v_n} w_n\right)^2 \quad .$$

The uncertainties w_i should be expressed as confidence intervals, such as "the mean of the measurement will be within $\pm w_i$, y% of the time." Then the mean of R will also be within $\pm w_R$, y% of the time. The only important restriction on the above equation is that the uncertainties in each of the variables must be independent.

The minimum allowable accuracy for time of measurement is within 5 minutes of actual time for all recording systems (IAEA, 1980; USNRC, 1980). For analog systems, the allowable accuracy is ± 10 minutes, ANS (1984).

Open structure towers are recommended for the mounting of sensors as they are likely to generate a smaller wake downwind and less overall lateral and upwind flow distortion than solid towers (NCAR, 1984). The sensors should be mounted on booms which should face into the prevailing wind. The booms themselves should be a minimum of 1 and a maximum of 1.5 tower widths at the height of measurement. A boom extended much further than 1.5 tower widths is likely to become unstable, flexible and difficult to service (NCAR, 1984).

The elements to be measured will be considered individually in the following sub-sections. It is beyond the scope of the project to assess, or make intercomparisons of, specific instruments. General and specific information on

meteorological instrumentation may be found in such publications as Mazzarella (1978), Met. Office (1981), NCAR (1984) and WMO (1971). Before dealing with individual measurements, the following is a glossary of terms commonly used in meteorological instrument specifications:

Accuracy - The degree with which an instrument measures a variable in terms of an accepted standard value or true value; usually measured in terms of inaccuracy but expressed as accuracy.

Damping ratio - A constant which describes the performance of a wind vane in response to a step change in wind direction. It is calculated from the relative amount of overshoot on two successive swings (half cycles) of a decaying oscillation.

Delay distance - The length of air flow past a wind vane required for the vane to respond to 50% of a step change in wind direction; expressed in feet or meters and calculated from delay time multiplied by wind tunnel speed.

Distance constant - The length of fluid flow (gas or liquid) past a sensor required for the sensor to respond to 63.2% of a step change in speed; expressed in feet or meters. For anemometers, this value is calculated from time constant multiplied by wind tunnel speed.

Error - The algebraic difference between the indication by an instrument and the true value of the measured signal.

Resolution - The smallest change in the environment that causes a detectable change in the indication of the instrument (compare to sensitivity).

Sensitivity - The ratio of the output of an instrument to the input value (e.g., a rain gauge with a sensitivity of 1 tip per 0.01").

Starting threshold - For an anemometer, the lowest speed at which a signal is measurable. For a wind vane, the lowest speed at which the vane when released from a position 10° off the wind tunnel centreline moves within 5° of the centreline.

Time constant - The time required for an instrument to register 63.2% of a step change in the variable being measured.

2.1 Wind Measurements

Measurements of horizontal wind speed, direction, and standard deviation of direction σ_θ, are required at the 10 m and 50 m levels (unless the effective release height is significantly different from 50 m). Measurement of the vertical wind component should also be considered on a trial basis. The following specifications are recommended for digital system accuracies for time-averaged values (US NRC, 1980; and IAEA, 1980):

Wind speed: Accuracy ± 0.25 $m \cdot s^{-1}$ for speeds less than 11 $m \cdot s^{-1}$ with a starting threshold of less than 0.5 $m \cdot s^{-1}$.

Wind direction: Accuracy ± 5° of azimuth with a starting threshold of 0.5 $m \cdot s^{-1}$.
For measurement of σ_θ a damping ratio of 0.4 to 0.6 inclusive is required, with a deflection of 15° and delay distance not to exceed 2 m.

For analog systems the accuracy should be not more than 1.5 times those for digital and this should include the reduction of the data to digital form.

As well as meeting the above specifications, selection of a system should take into account proven long term reliability, ease of maintenance and the ability to maintain calibration. The Bendix-Friez aerovane was recommended by NWG (1982).

It is recommended that the wind speed and wind direction should be sampled at 3 second intervals and a mean and variance of the signals calculated and recorded on-line at both 3 minute and 60 minute intervals (NWG, 1982). The data system should also be able to analyse the signals over a time interval of arbitrary length. No smoothing of the time series should be done prior to forming the standard deviation.

For σ_θ, it is recommended that wind statistics based on a 3 minute (or shorter) sampling duration be gathered for sites likely to experience intermittent pollutant concentrations (Hoffnagle et al., 1981). These σ_θ values can then be combined to match pollutant release intervals in order to model time-integrated concentration fields. For hourly standard deviation values Hoffnagle et al. (1981) gave a requirement for 360 samples to achieve an accuracy within 5-10% but this was thought by some of the workshop members to be a conservative number with fewer values needed in most instances.

2.2 Temperature Measurements

As with the wind sensors, the temperature sensors should be mounted on booms at the 10 and 50 m height. Booms are necessary in order to avoid measuring the temperature of the air locally heated or cooled by the tower structure. The temperature sensors must also be shielded from radiational heating and cooling and from precipitation. Aspirated radiation shields are recommended by (US NRC, 1980). The shields should point downwards or laterally towards the north (to minimize direct solar heating errors).

The following specifications for accuracy of the system are recommended (US NRC, 1980; IAEA, 1980):

Temperature	± 0.5° C
Temperature difference	± 0.1° C

Matched sets (i.e., measured values at any given temperature would be to within ± 0.1°C of each other although actual error in temperature measurement may be ± 0.5°C) of platinum resistance temperature sensors are preferred by NWG (1982) but the working group gave thermistors as an alternative if the calibration stability can be shown to be at least as good as that of resistance bulbs.

The temperature and temperature difference should be recorded at 3 and 60 minute intervals (NWG 1982).

2.3 Precipitation

As mentioned in the previous section, because of the spatially non-uniform distribution of rainfall and the imprecise knowledge of washout co-efficients, it should be sufficient to use rainfall rates measured at a station near the site. If no nearby precipitation data are available, a gauge is necessary on-site. It should meet the following specifications (US NRC, 1980): a recording rain gauge with a resolution of 0.25 mm. The accuracy of the recorded value must be within ± 10% of the total accumulated catch.

The collector should be located so that obstructions do not interfere with the collection of precipitation and a heater system provided to ensure a proper measurement of frozen precipitation (i.e., frozen precipitation is melted before measurement).

Precipitation should be recorded on a cumulative basis at least once an hour.

2.4 Radiation

In the absence of a climatologically representative source of radiation data, a measurement of solar radiation and net radiation on-site should be considered (see Chapter C, Section 8). A measurement of incoming solar radiation is required for obtaining an estimate of the convective velocity scale w_* and together with a measurement of net radiation would also give the additional option of using the STAR method for stability classification (IAEA, 1980; see Appendix A).

The following specifications are recommended for radiation measurement (Hoffnagle et al., 1981):

For a pyranometer: accuracy 50 $W \cdot m^{-2}$
resolution 10 $W \cdot m^{-2}$
time constant (63% recovery) 5 s

For complimentary net radiometer a response time of between 0.5 and 1 minute is specified.

Radiation sensors should be mounted rigid and level and free from obstruction in the plane of the sensing element. It is especially important that no obstruction casts a shadow on a solar radiation sensor (NCAR, 1984).

3. Data Monitoring and Recording

For data acquisition, a dual recording system, consisting of one digital system and an auxilary analog system is recommended (US NRC, 1980; ANS, 1984). The outputs from both systems should be checked for comparability. Wind speed and direction analog recorders should be of the continuous strip chart recording type while multi-point strip chart records are sufficient for the other parameters.

The data should be available for monitoring in the reactor control room and direct interrogation of the system should be possible from an emergency operations centre or a designated AES facility. This has already been discussed in Chapter B, Section 3. The basic reduced data should be averaged over a period of 1 hour and stored on magnetic tape. The format to be used should be decided upon by consultation with AES to achieve compatability with the national climate data archive.

The basic reduced data should be compiled into monthly and annual joint frequency distributions of wind speed and wind direction by stability class (ANS, 1984; IAEA, 1980; and US NRC, 1980). Calms may be treated as a separate class with no wind direction or distributed in all wind directions in proportion to the frequency of the lowest wind speed classes.

A set of raw analog or digital data should be maintained in a retrievable form for a period of five years and reduced data should be retained for the life of the plant (ANS, 1984).

4. Maintenance, Quality Control and Assurance

Quality control problems of meteorological measurement programs were addressed in US NRC Information Notice 84-91 (1984). It had been found that some meteorological programs had not been operated or maintained to ensure the availability of high-quality meteorological data for use in emergency response and in assessment of the radiological impacts of routine and "off normal releases." The two major concerns were availability of sufficient data and availability of valid data. Examples given included a site with only 50% availability within the required accuracy specifications, prolonged outages, degradation of instruments, misalignment of wind direction sensors and problems with measuring temperature difference due to failure of aspirators or misorientation of the sensor shields. The need for adequate maintenance and quality control and assurance programs is therefore obvious.

With the above comments in mind, reliability and proven record of performance should be an important factor in selection of the meteorological system. The system should be protected from lightning strikes or electrical surge in power lines by grounding and provision of surge protection devices on the incoming power lines and signal lines (ANS, 1984). Protection and consideration should also be given from environmental conditions such as icing, sea spray and air pollution. An adequate spare part inventory should be maintained.

Routine maintenance should be scheduled such that a 90% recovery rate for wind speed and direction and stability is possible and a log of all inspection, maintenance and calibrations should be kept as a permanent record.

The meteorological measurement system and associated controlled environment for the equipment should be connected to a power system that is supplied from redundant power sources (US NRC, 1980). In the event of failure of the primary system a backup system should be available. An independent measuring system for the 10 m wind speed, direction and standard deviation would be capable of providing an estimate of transport wind velocity and diffusion parameters σ_y and σ_z necessary for model input. This could be a permanent fixture on the site, but not part of the primary tower system, or it could be a mobile unit.

For complex sites backup measurements at more than one location may be necessary. Changeover time should be less than 5 minutes (US NRC, 1980) and the backup system must also have the necessary communication links to ensure direct interrogation capabilities.

Calibration of instruments and the system is recommended on at least a semi-annual basis or as necessary (US NRC, 1980; ANS, 1984). The Tennesse Valley Authority have developed a schedule of regular calibration for meteorological sensors and data collection system with traceability to the National Bureau of Standards being maintained whenever possible for quality control of the calibration data (Hamby et al., 1979).

Quality control of the raw data should be incorporated into the programs for computing mean values and other statistics. Alp et al. (1982b) have produced a program for statistical analysis of tower data which includes a quality control of temperature, wind speed and wind direction data. For example, for temperature, the following test is applied:

- A least square fit of a straight line is applied to the hourly data (T_i)
- The standard error of estimate is calculated (SE)
- The predicted value (T_p) is computed using the fitted line
- If $| T_i - T_p | > 2 \times SE$ then the value T_i is flagged and not included in the calculation of the hourly mean.

E. SUMMARY OF RECOMMENDATIONS

This section contains a summary of the major recommendations made in the report. External references, given previously, will not be repeated here.

- At least one instrumented meteorological tower of height 50 m should be operated continuously at the site. This is required for accurate forecasts during actual emergencies, and not for normal operation or design postulated accidents.
- As a minimum, measurements of horizontal wind speed, direction and standard deviation, and temperature should be made at 10 m and 50 m (effective source height). The requirements for, and accuracy specifications of the instruments needed to measure these and other desirable and possibly necessary (if no representative alternative data sources are available) meteorological parameters are given in Table E.1.
- It is recommended that error propagation analyses be conducted to determine the implications of instrument inaccuracies on the accuracy of model predictions.
- The horizontal dispersion parameter σ_y should be determined by formulae (adjusted for the specific site) from a measure of the standard deviation of horizontal wind direction σ_θ, except that if the wind speed is below 1.5 $m \cdot s^{-1}$, it should be determined by tables or charts via a stability

TABLE E.1 Summary of Meteorological Instrumentation Recommendations

Input Parameter	Required for	Meteorological Measurement Needed to Obtain Input Parameter	Required Accuracy of Measurement
Average transport wind speed and direction Standard deviation of horizontal wind direction σ_θ	Direct model input Calculation of σ_y	Measurement of wind speed and direction at 10 m and 50 m (effective source height). See above (not reliable for wind speeds < 1.5 $m \cdot s^{-1}$).	Speed: ± 0.25 $m \cdot s^{-1}$ for speeds less than 11 $m \cdot s^{-1}$ Threshold: < 0.5 $m \cdot s^{-1}$ Direction: ± 5°, resolution 1° Damping Ratio: 0.4 to 0.6, inclusive with a deflection of 15° Delay Distance: not to exceed 2 m
Mixed layer height, h_i	Direct model input	Values should be determined using an acoustic sounder during a site survey covering all seasons and times of day. Estimates can then be made taking into account prevailing meteorological conditions. Consideration should be given to maintaining an acoustic sounder that would be readily available for use during emergency situations.	
Ambient air temperature Vertical temperature gradient dT_a/dz.	Air density determination Determining a stability Classification	Matched temperature sensors, sensors at 10 m and 50 m (effective source height).	Temperature: ± 0.5°C Temperature Difference: ± 0.1°C
Atmospheric Stability Classification	Calculation of σ_z (and σ_y for wind speed < 1.5 $m \cdot s^{-1}$)	By $\frac{dT_a}{dz}$ as defined above; then using tables.	
Meteorological roughness length, z_0	Direct model input	Determined by assessment of surrounding terrain and land use. More than one value may be required if site is non-homogeneous with respect to wind direction. Allowances made for changing ground cover (season).	
Hourly precipitation data	Obtaining washout coefficient	Estimates from gauges within the national observation network in the surrounding area. If no nearby representative station; recording rain gauge on-site recorded on cumulative basis at least once per hour.	Resolution: 0.25 mm Accuracy of recorded value within ± 10% of total accumulated catch
Convective velocity scale, w_*	Used in convective boundary layer model	Estimation from values of incoming solar radiation. Use data from a nearby synoptic observing station. If no nearby representative station, measure solar radiation on-site.	Pyranometer: accuracy 50 $W \cdot m^{-2}$ resolution 10 $W \cdot m^{-2}$ time constant (63% recovery) 5s Complimentary net radiometer, response time between 0.5 and 1 minute

classification obtained from measurement of the vertical temperature gradient dT_a/dz. The vertical dispersion parameter σ_z should be determined from tables or charts via a stability classification obtained by a measurement of the vertical temperature gradient dT_a/dz.

- The tower should be sited to represent as closely as possible the same meteorological characteristics as the region into which any airborne materials will be released and in an area where natural or man-made obstructions or plant operation will have little or no influence on the meteorological measurements. The terrain around the base of the tower should be kept clear of ground cover of tree growth.

- Open structure towers should be used. The sensors should be mounted on booms which face into the prevailing wind and are of length a minimum of 1 and maximum of 1.5 tower widths at the height of measurement.

- At coastal sites the characteristics of both the mixed boundary layer and the unmodified air above need to be determined. This may require a secondary tower(s) and an additional instrumentation level on the primary tower.

- In irregular terrain, characteristics of both the lower regime where winds are locally disturbed by the terrain and the undisturbed upper regime need to be determined if diffusion is likely to take place from one regime to the other.

- Both digital and an auxiliary analog recording systems should be used. Time accuracy should be within 5 minutes of actual time for all recording systems.

- Both digital and an auxiliary analog recording systems should be used. Time accuracy should be within 5 minutes of actual time for all recording systems.

- Sampling time for digital wind and temperature measurements should be at 3-second intervals and the mean and various of the signals calculated and recorded on-line at both 3 minute and 60 minute intervals.

- The basic reduced data should be averaged over a period of 1 hour and stored on magnetic tape. The format to be used should be compatible with that used by AES for the national climate data archive.

- The data should be available for monitoring in the reactor control room and direct interrogation should be possible from an emergency operation centre in a designated AES facility.

- A set of raw analog or digital data should be maintained in a retrievable from for a period of five years and the reduced data should be retained for the life of the plant.

- The system should be protected from lightning strikes, electrical surges and other detrimental environmental conditions such as icing, sea spray and air pollution.

- An adequate spare part inventory should be maintained.
- Routine maintenance should be scheduled such that a 90% recovery rate for wind speed and direction and stability is possible.
- Calibration of instruments and the system should be carried out semi-annually.
- A log of maintenance, inspection and calibration of instruments should be kept as a permanent record.
- The meteorological measurement system should be connected to a power system supplied from redundant power sources.
- A back-up system supplied from an independent power source and capable of measuring at least the 10 m wind speed, direction and standard deviation should be available on site. The system must have the necessary communication links for direct interrogation. The changeover time from primary to back-up system should be less than 5 minutes.
- Quality control of the raw data should be incorporated into the programs for computing the mean values and other statistics.
- These recommendations should be updated periodically to keep pace with refinements in modelling and measurement techniques.

F. CONCLUSIONS AND FUTURE CONSIDERATIONS

The recommendations made in this report are based on a review of those made by other nuclear regulatory bodies and current literature concerned with dispersion modelling, measurements techniques and instrumentation. It was not within the scope of this project to actually test any models, techniques or instruments.

Well-tried and proven techniques and instruments have been recommended rather than those which may appear theoretically superior but lack long term field tests. The aim of the study was to determine "adequate" meteorological data for safety analysis for normal operation, design postulated accidents, and emergency conditions. It is considered that the recommendations made are adequate for the dispersion models which are currently being used.

Probably the most significant development with regard to instrumentation will be an increase in the use of remote sensor devices such as SODAR, LIDAR and Doppler techniques. These systems have not yet been used on a prolonged routine basis but their use in individual projects (for example see EPRI (1982a) and Kerry (1982)), indicates that they may soon take over from conventional meteorological sensors in providing the major input parameters for atmospheric dispersion models. There will, therefore, be a need to periodically update the recommendations for adequate meteorological monitoring standards as improved techniques become generally accepted.

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METHODS FOR OBTAINING σ_y AND σ_z

This Appendix presents a brief review of the commonly used methods for obtaining the dispersion parameters σ_y and σ_z. These methods are compared and one method is recommended for this study. The required input parameters for the recommended method are identified.

The various methods of obtaining values of the horizontal and vertical dispersion parameters σ_y, σ_z from meteorological measurement have been discussed at length in the literature but as yet there seems to be no consensus as to which methods are currently most suitable. Recent comparison of turbulence classification schemes include those of IAEA (1980), Mitchell (1981) and Sedefian and Bennett (1979). The methods themselves will neither be reviewed in detail nor has a detailed assessment of their relative merits been possible within the scope of this project. However a brief overview of some of the more commonly recommended methods for obtaining σ_y and σ_z will be given together with some of their advantages and limitations leading to a recommended method for the purposes of the present study.

1. Methods for Obtaining σ_y

   (a) Directly by formulae from measurement of horizontal wind direction standard deviation σ_θ.

Recommended/Used by: Canadian NWG, AMS Workshop.

References: Davis et al. (1985), Hanna et al. (1977), NWG (1982), Pasquill (1976), Sedefian and Bennett (1979).

Advantages:
- It is a direct indication of horizontal dispersion.
- It can be directly obtained from formulae - results not "quantised" as in stability classifications.
- It can be used irrespective of surface roughness and for sampling times up to 1 hr.

Limitations:
- It is not reliable in low wind speeds (< 2 m s^{-1}) due to inaccuracies in measurement of σ_θ.
- A correction for the height dependence of σ_θ may be necessary if elevated measurements are used to define the surface layer.
- Lack of reported "field tests" but see Davis et al. (1985).

   (b) From measurements of σ_θ to define a stability class, then use Pasquill/Gifford/Turner (PGT) or similar curves.

Recommended/Used by: ANS (For wind speeds > 1.5 m s^{-1})

References: Alp et al. (1982a), ANS (1984), IAEA (1980), Sedefian and Bennett (1979), US NRC (1980).

Advantages:
- σ_θ is a direct measure of horizontal dispersion.
- It can be used irrespective of surface roughness and for sampling times up to 1 hr.

Limitations:
- The values of σ_θ are quantised into classes (true for all stability class methods).
- It is not reliable in low wind speeds (< 2 m s^{-1}).
- A correction for the height dependence of σ_θ may be necessary if elevated measurements are used to define surface layers.
- The intervals defining stability classes under stable conditions (E - G) are often narrow and misclassification may result as these conditions are most likely to occur when wind speeds are low.
- The values of σ_θ corresponding to stability class are site specific.

(c) From measurement of the vertical temperature gradient dT_a/dz to define a stability class then use PGT or similar curves.

Recommended/Used by: US NRC, ANS (for wind speeds <1.5m s^{-1}), TVA

References: Alp et al. (1982a), ANS (1984), Hanna et al. (1977), IAEA (1980), US NRC (1980).

Advantages:
- It is easy to measure even in low wind speeds.
- It has been widely used.
- It is reliable for stable conditions when dispersion is most adverse for low-level releases.

Limitations:
- It is more characteristic of vertical turbulence.
- It is not reliable for unstable conditions or for elevated releases.
- It is known to greatly underpredict σ_y for very light wind speeds.
- The upper sensor may, on occasion, be above the boundary layer in stable conditions.
- Stability classifications used are site specific.

(d) Use of Pasquill-Turner Stability Classification and STAR (Stability Array) Program to define stability class then use PGT curves.

Recommended/Used by: NWG (Alternative method if dT_a /dz not available).

References: Alp et al. (1982a), IAEA (1980), NWG (1982).

Advantages:
- If there is a nearby synoptic meteorological station its observations of insolation and/or cloud cover and base height may be used.

Limitations:
- In addition to 10 m wind speed, observations of cloud cover and ceiling height or incoming solar radiation and net radiation are required if there is no nearby representative meteorological station
- There are some uncertainties in classification with less precision in the classification of stable conditions than of unstable conditions.
- The classes were based on experiments at one site which was very different in character from sites at which current Canadian reactors are located.

(e) Use of Richardson Number R_i, Bulk Richardson Number, R_{ib}, or Monin-Obukhov Length, L.

Recommended/Used by:

References: Alp et al. (1982a), IAEA (1980), Irwin and Binkowski (1981), Sedefian and Bennett (1979).

Advantages:
- They account for mechanical and thermal turbulence. Therefore stability is better classified by including wind speed as additional input.

Limitations:
- R_i includes a measure of the wind speed difference du which requires two measurements and as the final expression includes a $(du)^2$ term, large errors may result.
- The height intervals for dT and du should be infinitesimally small. Errors will be introduced when wind and temperature profiles deviate from their "ideal" forms as happens in some stable situations.
- The direct calculation of L requires values of the surface heat flux and friction velocity which are difficult to measure. Otherwise it is obtained using values of R_i or R_{ib}.
- The methods have not been well tested.

2. Methods for Obtaining σ_z

(a) Measurement of vertical wind direction standard deviation σ_ϕ

Recommended/Used by: Raynor et al. (1980), Karlsruhe Nuclear Research Centre.

References: NWG (1982), Raynor et al. (1980), Shamsaldin (1984).

Advantages:
- A direct method of vertical turbulence.

Limitations:
- Long-term reliability of the instrumentation used to measure σ_ϕ has not yet been proven in an operational setting.
- Formulae for a direct relationship between σ_ϕ and σ_z have not yet been widely tested. Therefore, a stability classification must be obtained.

(b) Measurement of the vertical temperature gradient dT_a/dz to define a stability class, then using PGT or similar curves.

Recommended/Used by: US NRC, ANS, NWG.

References: Alp et al. (1982a), ANS (1984), Hanna et al. (1977), NWG (1982), Raynor et al. (1980), US NRC (1980).

Advantages:
- dT_a/dz responds to thermal turbulence.
- It is easy to measure even in low wind speeds.
- It has been widely used.
- It is reliable for stable conditions when dispersion is most adverse for low-level releases.

Limitations:
- It is not reliable for unstable conditions or for elevated releases.
- The upper sensor may, on occasion, be above the boundary layer in stable conditions.
- Stability classifications used are site specific.

(c) Measurement of horizontal wind standard deviation σ_θ to determine a stability class, then using PGT or similar curves.

Recommended/Used by: -

References: Alp et al. (1982a), IAEA (1980), Mitchell (1982), US NRC (1980).

Advantages:
- One measurement of the horizontal wind standard deviation can be used to determine both σ_y and σ_z.

Limitations:

- σ_θ is more characteristic of horizontal disperion.
- Some modification to stability classes is needed during night time.
- It is not reliable in low wind speeds (< 2 $m \cdot s^{-1}$).
- A correction for the height dependence of σ_θ may be necessary if elevated measurements are used to define the surface layer.
- The intervals defining stability classes under stable conditions (E and F) are often narrow.
- The values of σ_θ corresponding to stability class are site specific.

For measurement of σ_z using Pasquill-Turner/Star and Richardson Number/Bulk Richardson Number/Monin-Obukhov Length methods, see comments made under measurement of σ_y.

3. Comparison of Methods and Recommendation

Methods which determine σ_y and σ_z from independent measurements appears to be superior to methods that rely on only one indirect measurement to obtain σ_y and σ_z such as the dT_g/dz method recommended by US NRC. For obtaining a value of σ_y, using the horizontal standard deviation of wind direction, σ_θ, is recommended by both NWG (1982) and ANS (1984).

NWG recommend direct calculation of σ_y from σ_θ using Pasquills (1976) formulae and this was also recommended by the AMS Workshop (Hanna et al., 1977). ANS (1984) recommend calculation of σ_y via stability class using the classification given by US NRC (1980). However, at low wind speeds measurement of σ_θ is unreliable. The lower wind speed limit for reliable measurement of σ_θ is given as 2 $m \cdot s^{-1}$ by IAEA (1980) and 1.5 $m \cdot s^{-1}$ by ANS (1984). At speeds below 1.5 $m \cdot s^{-1}$ ANS recommend that dT_g/dz should be used to obtain σ_y via a stability classification. However, this procedure will result in a conservative value of σ_y which may be considered unduly restrictive whenever plume meandering occurs. IAEA (1980) suggest that following field investigations, the normally estimated value of σ_y for wind speeds less than 2 $m \cdot s^{-1}$ may be increased by a factor of four. NWG recommend the use of dT_g/dz for assigning a stability class should the value of σ_θ be unavailable.

The direct measurement of the vertical dispersion parameter, σ_z, via the standard deviation of the vertical wind velocity σ_ϕ has not yet been generally recommended although it has been used as the basic parameter for stability classification at Karlsruhe Nuclear Research Centre, West Germany, (Shamsaldin, 1984). Instruments for measuring vertical wind velocity, including the Gill U-V-W anenometer (or similar fast response instruments), should be operated continuously to test their ability to provide reliable operational measurements of vertical velocity as recommended by NWG (1982). The validity of a relationship between σ_ϕ and σ_z has not yet been established. Current methods use a measure of σ, to obtain σ_z via a stability category.

ANS (1984) and NWG (1982) recommend the use of dT_a/dz to calculate a stability category and the latter then recommend the use of the semi-empirical curves of Smith (1972) and Hosker (1974) be used for obtaining σ_z since these curves take explicit account of the effects of surface roughness on the dispersion process. dT_a/dz can be used at all wind speeds and should be adequately conservative at low wind speeds.

The dT_a/dz method recommended by US NRC has come under much criticism since it was first recommended in 1972 (US NRC, 1972). However, many studies concentrate on making intercomparisons between it and other methods of obtaining the diffusion parameters rather than actual dispersion experiments. Until the instrumentation and formulation for calculating σ_z directly from σ_ϕ has reached an acceptable level of reliability or another single method has been shown by experiment to be consistently superior, the relative simplicity of the dT_a/dz method justifies its use for obtaining σ_z and as a general backup technique for low wind speeds or possible windvane failure.

In summary, based on the above discussions, the recommended methods for determining σ_y and σ_z are as follows:

(a) σ_y should be determined by formulae from measurements of the standard deviation of horizontal wind direction σ_θ, except when the wind speed is below 1.5 $m \cdot s^{-1}$ in which case it should be determined via a stability classification from measurement of the vertical temperature gradient dT_a/dz.

(b) σ_z should be determined by via a stability classification from a measurement of dT_a/dz.

The measurement of horizontal wind speed, direction and standard deviation at 10 m and the effective source height (50 m, NWG, 1982) and the temperature difference between the two heights dT_a will include all the measurements needed for determination of σ_y and σ_z. Consideration should also be given for including measurement of the vertical wind velocity and standard deviation on a trial basis.